LCA Methodology

Parameterised Inventories for Life Cycle Assessment

Systematically Relating Design Parameters to the Life Cycle Inventory

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Abstract

Background and Objective. Life cycle assessment (LCA) is a highly data intensive undertaking, where collecting the life cycle inventory (LCI) data is the most labour intensive part. The aim of this paper is to show a method for representing the LCI in a simplified manner which not only allows an estimative, quantitative LCA, but also the application of advanced analysis methods to LCA.

Procedure and Method. The method is based on two main components: Firstly the parameterisation of the life cycle inventory for complete product ranges, e.g. relative material composition (the parameterisation factor is product mass or product volume), relative manufacturing inputs and wastes (the parameterisation factor is production output, in number of items, mass or volume), inputs, wastes and emissions during use (the parameterisation factors are efficiency, emissions per unit energy converted, etc.). Secondly, the parameterisation factors are related to design parameters, e.g. the efficiency of three-phase induction motors increase as the torque output increases and decreases with the number of poles, while the mass of the same induction motor increases with torque. Determining these relationships is initially labour-intensive, but only has to be done once for a product type and it is just a matter of fitting appropriate models after the collection of the relevant data. Also, required data is not impossible to come by, and respective industries publish many of the relevant data for marketing and design purposes. Due to the wide variety of products – whereby here the term 'product' is used in the widest sense and can be a component, an assembly, a consumer product or service – the relationships are represented as ranges with upper and lower limits. One of the limits represents 'the best practically possible' and is a good indication of what the technologies' capabilities are at the time. Top-down approaches allow the approximate determination of manufacturing inventories for product ranges. Bringing the two components together, the LCA analyst can use known design parameters and so quickly determine an estimate of the life cycle inventory, after which it is then a relatively simple step to carry out the full, approximate LCA. Furthermore, this method can be extended to include life cycle costing as an extension, to simultaneously assess economic aspects of the design.

Case Study. The method is further illustrated using a 3-phase asynchronous motor as an example and it is shown how the changing needs during the design process are utilised.

Discussion and Conclusion. The paper introduces the concept of parameterised inventories for the use in LCA, describes the general procedure of determining the relationships of the parameterised inventories to design parameters and outlines future developments enabled by this method of inventory representation. The novel parts of the method are a simplified, but quantitative LCA method. For the first time this enables parametric studies and sensitivity analysis, not only for varying material compositions, but varying the underlying design parameters in complex interactions, and finding optimised sets of solutions for those design parameters to achieve one or more optimised criteri(on)a.

Perspective. The full potential of the method as an analysis tool, especially in the early design phases, will be reached in an integrated engineering environment, where relevant LCA and cost data are automatically and systematically exchanged along the supply chain.

Keywords: Modelling; life cycle inventory (LCI); parameterisation; simplified LCA

Nomenclature

Item	Abbreviation	Item	Abbreviation
Life Cycle Assessment / Inventory	LCA/ LCI	Environmental Impact Assessment	EIA
Design Parameter	DP	Life Cycle Parameter	LCP
Parameterised Inventories	PI	Pre-Manufacturing phase	pm
Lower Limit / Upper Limit	LL, UL	Manufacturing phase	m
Specific Product Model	SPM	Use phase	u
Specific Product Range Model	SPRM	Post-Use phase (recycl., disposal, etc.)	pu
LL / UL Specific Product Range Model	LLSPRM, ULSPRM	LL / UL Generic Product Range Model	LLGPRM, ULGPRM

1 Background

Life cycle assessment (LCA) as such is not complex when looking at the single tasks one-by-one, but the sheer number of data elements that have to be collected, organised, verified and analysed result in LCA as a whole becoming complex. Consequently, the inventory analysis is the most data intensive part of LCA. To give an impression of the scale associated with compiling a life cycle inventory (LCI), it was estimated that an analyst may require some 10^4 to 10^5 or more numerical data elements for a complex product which will consist of thousands of unit processes [1]. This is due to the fact that it is difficult to establish a link between the geometric representation, which initially can be in the form of sketches on paper, and the inventory. It is furthermore extremely difficult and expensive to automatically extract LCI data from CAD information, since CAD systems lack required attributed information and LCI databases are incomplete and expensive, and descriptions are not standardised for reliable interfacing and identification.

LCA, in many cases, is prohibitively expensive for small and medium sized companies (SMEs), in the largest part because of the expenses incurred for establishing the LCI, and since the short and medium term benefits are difficult to quantify. There is a need for a methodology which makes LCA a more accessible analysis tool for SMEs in general and for assessing design concepts, because the early design phase is where life cycle assessment is most effective and where it is easiest to carry out changes and to reduce environmental impact [2].

2 Objectives

It is the aim of this paper to present a practical method of determining quantitatively an approximate LCA. The paper is structured to first give an overview of how the method is included in an LCA environment, while the latter parts describe details in a general manner and in a concrete manner through a simple case study.

The main concept behind this method is to use relationships between information that a designer can relate to, estimate and determine early during the design process (e.g. design parameters and usage parameters), and various parts of the LCI for a given product (which may be a component, a subassembly or an assembly) [3].

It will be shown that the analysis of life cycle inventory related parameters (Life Cycle Parameters, LCPs) of mass-produced standard machine elements, engineering parts, assemblies and products can be used to represent average, maximum and minimum inventories in relationship to design and usage parameters. A practical approach is outlined and an example illustrates some advantages and disadvantages of the method. A detailed description of the method can be found in [4].

The method of representing the LCI allows any environmental indicator to be used for the environmental impact assessment (EIA), thus completing the LCA process.

3 Procedure: From Design Parameters to Assessing the Life Cycle

In this paragraph, it is briefly described how the LCI modelling method is incorporated into an LCA-tool. The different stages required are described and the advantages and disadvantages are outlined. The LCA-tool has been implemented as a prototype software and case studies have been carried out for testing the procedure and programme [6].

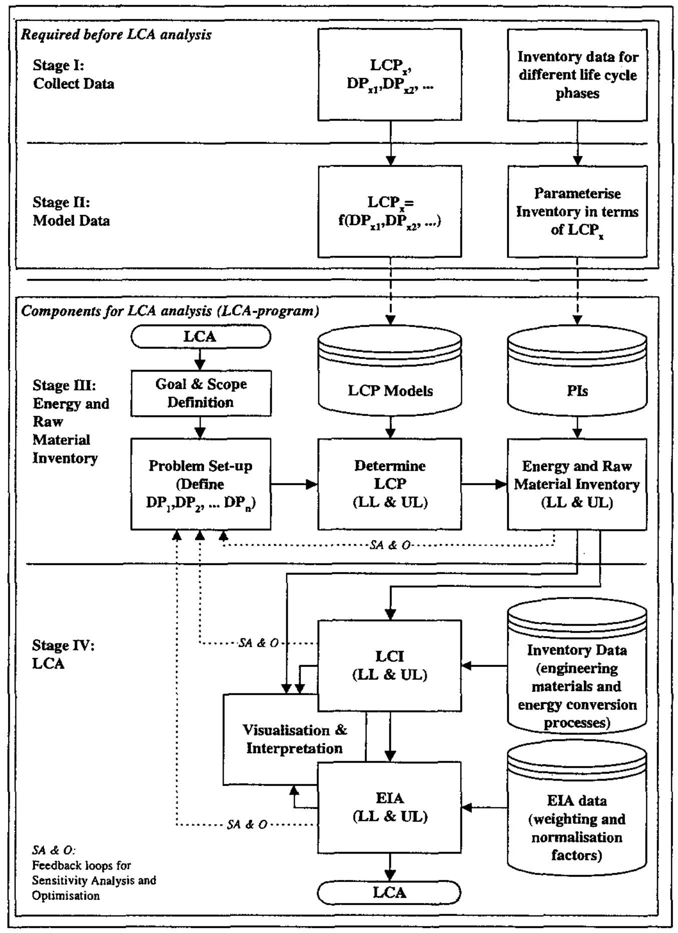

Fig. 1: Flowchart of how the LCP-models and PIs are used in an LCA tool (for abbreviations see text)

The flowchart (**Fig. 1**) depicts how the parameterised inventories (PIs) and the LCP-models are used to first estimate the energy and raw material inventory, which in turn is used to determine an approximate LCI, which is subsequently used as an input to an environment impact assessment (EIA). The stages required for the LCA are:

1. collecting data (for several products of a product class)
   - Design Parameters (DPs), describing properties relevant to sizing during the design process
   - Life Cycle Parameters (LCPs), describing properties that can be directly related to part of the life cycle inventory
   - life cycle inventory data
2. modelling the data (for a product class, or more detailed: for product families)
   - Parameterised inventories in terms of life cycle parameters (see paragraph 4.1.3)

- life cycle parameters as functions of design parameters (see paragraph 4.1.4)

3. determining the energy and raw material inventory
   - define DPs
   - determine upper and lower limits of LCPs (using DPs and LCP-model database)
   - determine and interpret upper and lower limits of energy and raw material inventory (using LCP and PI databases)
4. carry out an LCA
   - determine and interpret upper and lower limits of LCI (using energy and raw material inventory and a inventory database for engineering (raw) materials and energy conversion processes)
   - determine and interpret upper and lower limits of Environmental Impact Assessment (EIA) scores (using the LCI and an EIA database consisting of weighting and normalisation factors)

Stages 1. and 2. are required before the LCA can be carried out and they are labour intensive. They are the main focus of this paper while the latter stages are only briefly outlined. An effective implementation of this method requires a data exchange infrastructure between original equipment manufacturers (OEMs) and clients, who want to carry out simplified LCAs during the design process.

The figure further points out that the representation of the LCI via the PIs and the LCP-models allow sensitivity analysis and optimisation procedures to be added. The sensitivity analysis is carried out by varying the LCPs within lower and upper limit (LL and UL) ranges for given DPs and then analysing the effects on the LCI and the EIA-result. Optimisation procedures are more complex to implement. A promising method is the parameter space investigation (PSI) method described by Statnikov [7].

Sensitivity analysis and optimisation are unique features of this approach, since these procedures can only be implemented if the DPs and the LCI/EIA result are also linked in the modelling approach. Standard LCA approaches, in contrast, use a product's material and energy requirements either as direct input or as a simple correlation into the LCA programme, from which the LCI and EIA results are obtained, with no possible correlation to DPs.

Once the LCP-models are determined for a specific product class, the LCP-models may change with time in two ways:

1. the form of the equation and its constants may change in the case where significant technological change has taken place and the main underlying physical principal for achieving the main intended function has changed or
2. only the values for the constants change as the product undergoes incremental change with time

Depending on the *maturity* of the technology the rate of change of the models will vary over time: A mature technology, such as the internal combustion engine, will only change slightly in a given time; a maturing technology, such as the fuel cell, may see greater changes in the same time period.

Similarly, the PIs need to be validated from time to time and, depending on the maturity of the technology, the changes of the PIs vary.

4 Methods

4.1 LCI modelling method

The main point of this section is to illustrate the method of relating the LCI via so-called Life Cycle Parameter (LCPs) and Parameterised Inventories (PIs) to Design Parameters (DPs).

The LCI modelling method requires the determination of two distinct types of relationships:

1. Parameterising the inventories in terms of LCPs
2. Relating LCPs to DPs

The determination of these relationships between the different types of data results in models of varying complexity, depending on the desired detail and accuracy required and ultimately on the resources available. The aforementioned models are useful in the sense that they firstly 'compress' large amounts of inventory data and secondly relate DPs to the LCI, thus increasing the value of information, as depicted in **Fig. 2**. Furthermore, relating the DPs to the LCI enables the use of analysis tools, such as sensitivity analysis and optimisation, thus aiding the understanding between the choice of DPs and the LCI.

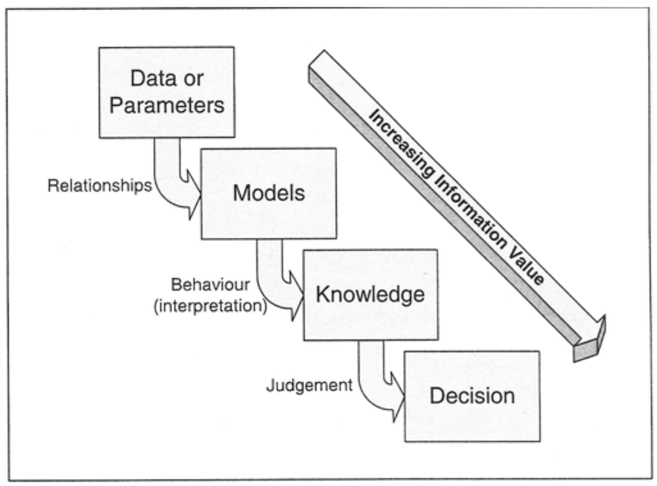

Fig. 2: The value of information [5]

4.1.1 Definition: Products

Throughout this article, the term 'product' refers to parts (e.g. machine elements, semi-products), subassemblies (such as a set of gears), assemblies (such as an induction motor), consumer products (such as a fan or a car) or larger systems (such as a manufacturing line). A product of one manufacturer may be the subassembly to another. It is seen as a relative definition and, where necessary, this will be clarified.

The products are of different complexity where the parts present the low complexity products and consumer products, and systems usually present higher complexity products. This method is based on modelling the LCI of low and medium complexity products, which are assembled in a modular fashion to represent products of higher complexity.

Furthermore, specific products belong to product classes, where the underlying technical principal is the same for all products in one product class. The abstracted product, representing a whole product class, is termed *generic product* in this paper (cf. section 4.1.3).

Finally, (mass-) products of one manufacturer are often part of product ranges (product families), where the similarity between the different products is usually significantly larger as compared to products outside of the product range, but belonging to the same product class. An example from the automobile industry would be the inherent similarity of Volkswagen-group cars based on the Golf platform, such as the VW Golf, Audi A3, Seat Leon, Skoda Octavia, and differences between Golf-class cars, such as the VW Golf, Ford Escort, Peugot 306 and Opel Astra.

4.1.2 Definition: Design parameters and life cycle parameters

Design parameters (DPs) are usually physical characteristics of the design of a machine element or assembly. The DPs, which are interesting within this context, have to fulfil the following criteria:

- In this context, the DPs must have a *significant relationship to at least one LCP*. For example, whether the casing of a machine is painted red or blue can be decided early during design, but it most probably bears little impact on the life cycle. On the other hand, whether the design is painted (or treated) at all, and if so, with which type of paint, will most probably influence the life cycle parameters more significantly.
- The DPs have to be parameters that can be *estimated at the early phase* of designing. For example, the power output of an electric motor can be estimated at an early stage, but may show that the physical dimensions that the motor must have are less obvious at this stage.

Life cycle parameters are defined as parameters that relate directly to the life cycle inventory of one or more life cycle stages. LCPs are not limited to a particular class of parameter, and include *physical* parameters, *temporal* parameters and discrete (*quantitative*, e.g. number of cylinders, number of valves per cylinder, and *qualitative*, such as petrol engine vs. Diesel engine) parameters. While it was said that the DPs are correlated to LCPs, the inverse is not always true, i.e. not all LCPs are related to DPs and therefore there are DP-independent LCPs.
LCPs should fulfil the following criteria:

- The LCPs main criteria are that they *relate to part of the LCI*. Ideally this means, determining and/or specifying values of all the relevant LCPs of a product, that an LCI can then be determined with general inventory data on engineering materials and energy generation processes.
- Some LCPs are *related to DPs*. The relationship can be of a continuous, semi-continuous (e.g. due to standardisation) or discrete nature.
- If the LCPs are described by qualitative data then these *discrete levels should be limited* to a sensible number by making assumptions.
- *DPs are not excluded* and may also be LCPs

To ensure practicality and validation, it may also be noted that the DP and LCP data should be obtained from publicly accessible data sources. This means that the manufacturing industry itself or third parties have an active interest in publishing this data or the data can be indirectly derived through established relationships to published data. It is of little use if the LCP is of a nature that product manufacturers are unable to supply data on the grounds of confidentiality or similar issues. Usually this is a question of how detailed the models are, as manufacturers may be able to supply general data, but are unable to disclose data on details. A practical issue is the sufficient amount of data for the models, since a lack of data makes error and uncertainty estimation difficult.

4.1.3 Assumption: Generic product and parameterised inventory (PI)

A product is seen as a '*generic product*', whereby the generic product displays average characteristics of one or more *product ranges*, which scale (linear or non-linear, continuous or discrete) with one or more LCPs. The generic product's inventories of the different life cycle stages (pre-manufacturing, manufacturing, use and post-use) are generalised in form of parameterised inventories (PIs). It must be accepted that all product designs are subject to physical principals and are limited by material properties and manufacturing methods. These constraints apply to all products and it is assumed that these constraints result in similarity between the products of the same product class. This similarity can be exploited to reduce data.

If the concept of the generic product can be accepted, then parameterising the generic product's inventory in terms of LCPs is uncomplicated. While there are several LCPs, a very important one is a product's mass. Inventories can often be parameterised in terms of product mass. For example the pre-manufacturing inventory can be related to the product mass. This can be simple linear relationships (as used in this paper), but more complex relationships are possible. In simple terms this means, if the mass of product A is known, then choosing the parameterised inventory for the product family, of which product A is a member, will yield the estimated material composition, the manufacturing inventory, etc.

For example, a simple linear relationship between the product mass – the LCP that is the parameter which is used for parameterising the inventory – and the material composition (i.e. the pre-manufacturing inventory) of an induction motor may be given as 8% Copper, 40% Dynamo Steel Iron, 35% Grey Cast Iron, 10% Steel and 7% other Materials (mostly plastics, insulation material). This is a simplified representation of the material composition, but often of sufficient detail for an approximate LCA. More complex relationships can be used if the gain in accuracy justifies the increase in the model complexity. Now, *only* the definition of the LCPs are required (here product mass) to approximate the absolute amounts of the materials.

Similarly, in the simplest case, the manufacturing inventory can also be approximated to be proportional to the product mass. An analysis of inputs, waste streams and product mass output for a factory – or ideally a number of factories producing products belonging to the same product type – for a

given period and an appropriate allocation is required for these figures. This linear relationship is then a 'relative manufacturing inventory', or the PI of the manufacturing phase, where the LCP is again the product mass.

The use-phase inventory is modelled using LCPs such as efficiency, usage characteristics and design life. Again the complexities of the relationships depend on the specific product modelled and the required accuracy, whereby the gain in accuracy must justify the increase in the model complexity.

There is scope to capture significant differences, e.g. when, for a type of product, most manufacturers generally include the uses of toxic substances, while some manufacturers have managed to exclude or significantly reduce the amount of the toxic substances, then these need to be distinguished by qualitative LCP. As mentioned before, these discrete levels of the qualitative LCP should be limited to a sensible number by making valid assumptions to ensure a practical compromise between simplicity and accuracy.

The parameterised inventory data is labour-intensive to gather and may include confidential information, but since it represents an averaged picture for a product range, industry is more willing to supply such generalised data as compared to the specific cases. In some cases theoretical analysis and practical considerations give a good indication of likely material compositions. Furthermore, collecting PI data for a whole product range is significantly less labour intensive compared to collecting average LCI data for all the specific products of a product range. This represents a substantial work reduction when carrying out LCAs.

4.1.4 Relating design parameters to a life cycle parameter

The LCPs, such as mass, efficiency, volume and usage times, of a product are related to design parameters. Depending on the product type, DPs are diverse and include torque output, number of poles, capacitance, storage capacity of a HDD, access times, resolution of a screen, manufacturing date and so on. The relationships between the LCP and the DP (or a number of DPs) are derived based on

- theoretical reasoning
- common practice and practical considerations (e.g. due to standardisation)
- empirical observations

In practice, it was found that with products of medium complexity, such as lead acid batteries or three phase asynchronous electric motors, it is practical to start by theoretically proposing a relationship and then using empirical data to adjust the mathematical function.

The relationships are usually expressed in an explicit form LCP = f(DP) or LCP = f(DP_1,DP_2,...,DP_n), which is a very compact representation of the data, as it covers a whole product range. It may be necessary to express the relationship in an implicit form, which in general is acceptable, but solving for the LCP for given DPs may pose difficulties.

4.1.5 Lower and upper limits (LL/UL)

After collecting relevant data, upper and lower limits of the LCPs in terms of the DPs are determined. In the case where the LCPs and the DPs are selected correctly, i.e. that there is a relationship between the two, then a banded region can be observed, as is illustrated in Fehler! Verweisquelle konnte nicht gefunden werden.

Here, the x-axis is designated with a DP. In general it may also be a combination of DPs, e.g. instead of LCP only depending on the DP 'Torque', the LCP may depend on a combination of DPs, such as 'Speed' times 'Torque' (= 'Power'). When mentioning upper and lower limits, it is possible to qualify the upper and lower limits depending on what the actual LCP is and how critical that LCP is on the total life cycle. By this it is meant that one line represents a *best case* and one a *worst case*. For example, if the LCP is mass and mass is a critical issue of the life cycle, then the upper limit is the worst case. On the other hand, the lower limit represents the best case, i.e. for a given DP the minimum mass (the LCP) is represented by the lower limit.

Usually the line representing the upper and lower limit cannot be related to theoretical considerations about the relationship of the DP and the LCP, but theoretical considerations offer a good start for the initial guess of the form of the equation.

The initial form of the equation may then be adapted on an empirical basis to include

1. less terms, by excluding the terms with little statistical significance regarding the model or
2. further terms, if the fit is not sufficient to capture the trend of the data

The upper and lower limit models can be determined for groups of data, such as to a product range of a manufacturer or indeed to all the products, describing the actual possibilities of what is produced.

The upper and lower limits in **Fig. 3** capture the range of an LCP for a given DP or a set of DPs. It is a representation of the technology's capability as a whole. This is used to determine the importance of the individual DPs on the LCI.

A simple example is: the more torque (a DP) an electric motor is required to produce, then the larger the mass (an LCP) of the motor. Another example is: the larger the overall power output (a DP) of the motor the better the overall efficiency (an LCP). These are overall trends and when analysing data from manufacturers it was found that there is a clear cut-

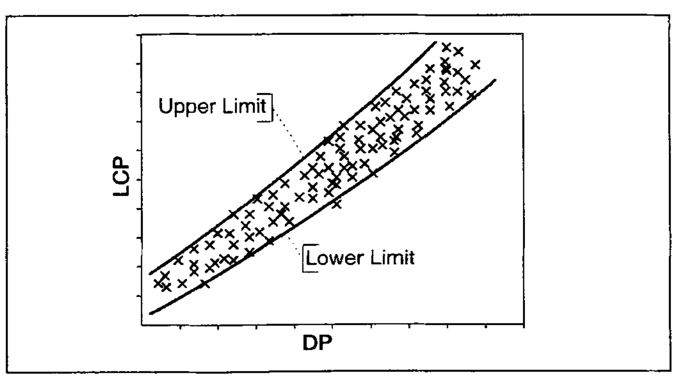

Fig. 3: Schematic illustration how data (crosses) are banded, so that an upper and lower limit can be determined [4]

off. The cut-off showed that there was no manufacturer who produces for a given output torque, a motor with a lower mass and for a given power, a motor with a higher efficiency. Many manufacturers produce worse, though.

4.1.6 Further refinement: Multiple DPs

Establishing the aforementioned relationships between DPs and LCPs, it is important to realise that they should:

1. correctly summarise the facts and
2. be simple enough for practical application.

This is true for any scientific law. In order to increase the accuracy of the relationships, the models may be expanded by including further DPs to describe an LCP. In **Fig. 4** the data is shown to be banded in three distinct narrower bands. These represent a second DP's influence, which can be incorporated into the model to give a more detailed representation of the LCP.

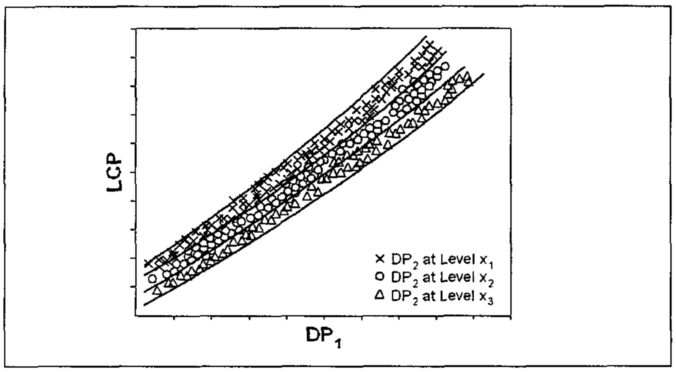

Fig. 4: Schematic illustration how data depends on a further DP which can be used for a more accurate grouping [4]

In **Fig. 5**, the band is narrower altogether since the LCP is plotted not against one DP, but against a function of DP_1 and DP_2. This may be repeated with further DPs to obtain more refined models. The validity of the other models is not compromised by this and they should be kept, as they represent the LCPs when not all the DPs are known.

This is a strength of this method in that it always offers a compromise between simplicity and accuracy. When a DP can be estimated, then it enables a more accurate estimate of the LCP. This is a useful feature for the continuous nature of the design process, i.e. as the design progresses and more DPs are fixed the more accurately the LCP can be estimated.

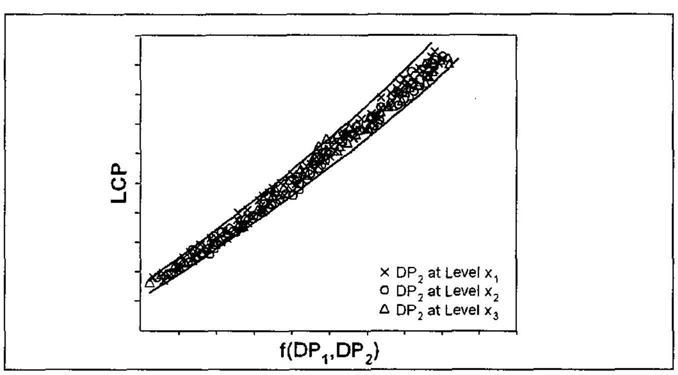

Fig. 5: Schematic illustration of how the LCP is not plotted as a function of one DP but as a function of DPs [4]

4.1.7 Further refinement: Modelling one manufacturer's product range

When looking at the data of one model range of one manufacturer then it can be observed that the points lie in a much closer band, which can be represented with one fit for the whole range (**Fig. 6**).

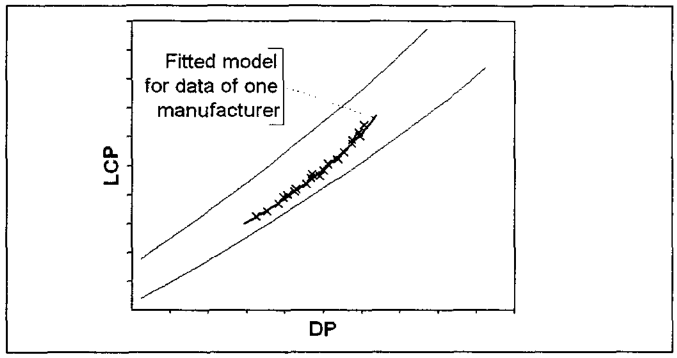

Fig. 6: Schematic illustration how data (crosses) of one manufacturer's product range lie in a much tighter band, which may be represented by one model [4]

Furthermore, the graph in **Fig. 7** illustrates that the model of the individual product range does not necessarily follow a line parallel to the lines representing upper or lower limits. It follows a line which is dictated by the actual realisation of a product by a manufacturer. Therefore, the models of the individual product range can be quite different to the models representing the upper or lower limits. Also, for obvious reasons, these models are only valid over the range for which data was available.

This information may be useful to compare different product ranges of one or several manufacturers in general terms, although the additional work that is required to generate the models is considerable.

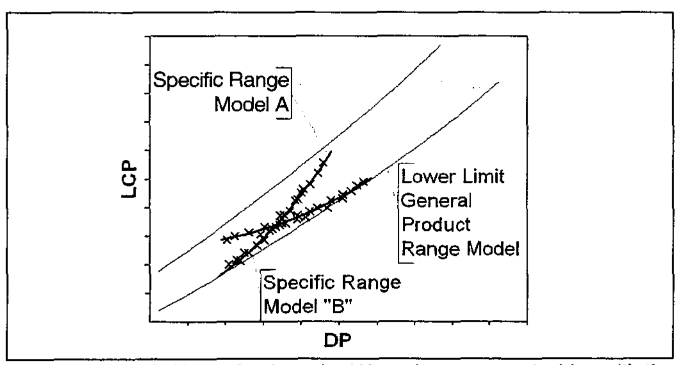

Fig. 7: Schematic illustration how the 'A' product range coincides with the LLGPRM for certain DP-range only, and the 'B' product range coincides with the LLGPRM for a different DP-range [4]

5 Case Study: Applying the Modelling Method: Induction Motor

In the following, the simple example will be expanded upon in more detail and a graphical representation of the relationship is used to illustrate the above. Three-phase, induction motors produced by 16 European manufacturers were analysed. A total of 2413 motors are included from 30 product ranges.

5.1 The parameterised inventory (PI) of a generic product

The parameter used for scaling the PI is mass. This is the most obvious choice in case of products such as an electric motor. Here, the PI is represented in percentage terms for the pre-manufacturing inventory and in energy units per unit product mass for the manufacturing inventory. The data given in **Table 1** werden. is an average from a few manufacturers only and the manufacturing PI is limited to energy consumption, therefore this data is intended for illustrative purposes only.

The specific primary energy in **Table 2.** was determined taking into account the energy mix and conversion efficiencies from the region of manufacture (Sweden). As this is data from only one manufacturer, further studies need to highlight the differences between various manufacturers and how these can be included into the PI for the manufacturing phase. A likely method is to use the region (country) as a distinguishing variable. The inclusion of further waste streams (e.g. auxiliary material input, solid, liquid and gaseous waste output) is an additional requirement.

5.2 Mass versus torque

The format of the equation was found from theoretical reasoning based on the concept of an output coefficient [8]. The actual coefficients of the equation where found from the data of the actual motors. The equation relating the LCP mass, m in kg, to the DP torque, T in Nm, is given in Equation 1. In this article, torque is the full load torque of the motor at its operating speed.

$$m(T) = a + b\,T^{c} \quad (1)$$

where for the lower limit, i.e. the lowest possible mass for a given torque, the constants are $a = 0.6590$, $b = 1.7920$ and $c = 0.8388$.

In **Fig.** 8, data for torque and mass, and the models representing the practical limits, are displayed. The upper limit is not as clearly cut as is the lower limit. This indicates that producing

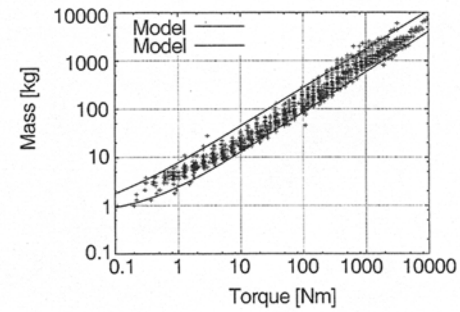

Fig. 8: Mass versus torque data (crosses) for induction motors. Models (lines) represent practical limits [4]

a motor with a torque/mass relationship below the lower limit is difficult and impractical for reasons such as material expense and manufacturing method. Therefore, manufacturers don't produce induction motors below the lower limit.

The wide range is also due to the fact that motors with cast iron casings were not distinguished from motors with aluminium casings. The data used did not clearly distinguish between the different cases in a consistent manner, so that this relevant DP had to be neglected.

5.3 Efficiency versus torque and number of poles

Similarly, as mentioned before, theoretical reasoning was used to propose the format of the equation while actual data from manufacturers was used to adapt the equation and determine the actual constants. The equation relating the LCP efficiency, η, to the DP torque, T in Nm, is

$$\eta(T) = \left(a + \frac{b\,T^{1-c}}{T}\right)^{-1} \quad (2)$$

where for the upper limit, i.e. the highest efficiency for a given torque, the constants are $a = 1.0187$, $b = 0.3194$ and $c = 0.4515$. The term $b\ T^{1-c}$ in Equation (2) represents the torque losses in terms of the output torque, T.

Table 1: Generic Product's Parameterised Inventory (PI) for the pre-manufacture of a three-phase induction motor (illustrative purpose only)

	Pre-manufacturing PI	
Material	**Part**	**% of Total Mass**
Copper	Stator, Rotor	9 ±1
Grey Cast Iron	Casing, Bearing Plate, Terminal Box, Foot	32 ±2
Dynamo Sheer Iron	Stator, Rotor	40 ±3
Steel	Shaft	10 ±2
Other	Insulation Materials	9 ±1

Table 2: Generic Product's Parameterised Inventory (PI) for the manufacturing phase of a three-phase induction motor (illustrative purpose only)

	Manufacturing PI (Sweden)	
Energy Carrier	**Specific Energy at Point of Use [Wh/kg$_{Product}$]**	**Specific Primary Energy [MJ/kg$_{Product}$]**
District Heating	464	2
Electricity	2506	20
Gas	121	1
Total		**23**

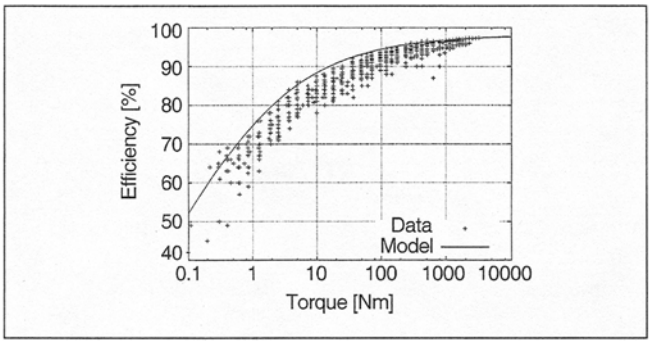

Fig. 9: Full load efficiency at nominal speed versus torque data (crosses) for 2-pole induction motors. Model (line) represents practical upper limit [4]

In Fig. 9, torque and efficiency data are displayed for 2-pole induction motors. The data illustrates that manufacturers cannot produce motors with an efficiency better than the upper limit model, but here are many motors with a worse efficiency.

6 Discussion

The method of carrying out estimative quantitative LCAs via modelling the LCI in terms of DPs and the concept of parameterised inventories enables the use of powerful analysis methods in novel ways with respect to LCA. Sensitivity analysis, parametric studies and optimisation can all be utilised with respect to underlying design parameters, and not just with respect to directly related parameters, such as design life, usage characteristics and the like.

6.1 Estimating the best possible

The mathematical models in the example from section 5 are the best case models for the whole product class (lower and upper limit generic product range models), i.e. the lowest mass and highest efficiency for a given torque, only for three-phase, induction motors. This represents the actual possibilities that product manufacturers have today, under optimum conditions. Other models for specific product ranges were produced that allow the analyst to specify a particular product range. These models represent more detailed cases, while the above models represent the induction motor as a generic product. This is of use when comparing two design concepts which are made up of different types of components. When comparing the design concepts, it is only fair to compare the best possible of one type of component with the best possible of the other type.

LCA will highlight whether a certain LCP is of significant importance, and if not then this LCP can be relaxed. If a sensitivity analysis LCA indicates that mass is not a significant DP with respect to the whole life cycle, for example, but efficiency is significant, then, from the perspective of LCA, a more efficient product should be chosen, even if it incurs a larger mass. At this stage it is helpful to use specific product range models. The designer can focus to satisfy the significant LCPs, by selecting a specific product which meets the criteria.

6.2 Adapting during the design process

The design process was classified into three levels of increasing detail [9]:

1. Concept phase
2. Embodiment phase
3. Detailing phase

One major consideration that was taken into account when the LCA method was developed was the changing nature of the design. At the early stages changes are inexpensive, but the definition of the design is relatively raw. As the design progresses to the embodiment and detailing phases the definition of detail of the design increases to a very high level, eventually sufficient for production, but the cost of change increases for each phase by an order of magnitude [10].

At early stages of the design process, generic product range models are used to evaluate a best and worst case. As the design becomes more detailed and as the initial analysis highlights the relevant design parameters, which need to be controlled, the analysis can move to more specific product range models (one manufacturer's product range), which are more accurate with respect to the specific product, both in terms of the parameterised inventory being more representative and the determined LCP being determined with a reduced deviation.

The method is therefore suitable for *quantitative* analysis even during the concept stage, although the LCI/LCA resulting difference between the upper and lower limit may be large. This difference will decrease with an increasing definition of the product and the application of more specific and therefore more detailed models. An analysis using only specific product range models during the early embodiment phase will result in sufficiently accurate LCI/LCA result set for decision making, which can be further verified by a detailed LCA during the late embodiment and early detailing phase.

6.3 Life cycle costing

The here introduced underlying modelling approach is also very suitable to be extended to include life cycle costing. During early stages of the engineering design process, it is common practice to estimate a product's cost from its correlation to the product's mass or to the material cost.

The macro scaling, or top-down approach, is a method for estimating cost at the early stage of the design phase by utilising the empirical fact that for related assemblies the final cost is approximately proportional to the product's weight [11]. A slightly different correlation is used to estimate the final product cost by relating it to the material cost. In this costing method, it is assumed that, if the product is similar in construction, the ratio of the material cost to the final product cost is then equal for all similar products [12]. Both these approaches represent a suitable extension, especially with respect to analysing the effect of DPs on cost (sensitivity analysis and optimisation).

The product weight is a modelled LCP and therefore scaling based on the product weight is a matter of obtaining current relative product cost data. This method is relatively crude, but practical and often used in industry. The relative material composition together with the LCP 'mass' gives an estimate of the absolute mass of the materials used. This can be used to estimate the material cost of the product and with data on the percentage share of the material cost of the overall product cost, the overall product cost can be estimated.

Estimating the cost of the components in relationship to LCPs, which in turn are modelled as functions of DPs, links the cost to design parameters. An integrated implementation of costing thus allows the designer to estimate the cost of changing of DPs on the overall life cycle cost.

7 Conclusions

This paper introduced the concept of utilising parameterised inventories for an approximate, but quantitative life cycle assessment. The procedure of determining a parameterised inventory, modelling life cycle parameters in terms of design parameters and utilising these models to determine upper and lower limits of the inventory is a practical method to estimate the life cycle inventory, ultimately expanding the analysis possibilities in LCA to include parametric studies and sensitivity analysis with respect to underlying design parameters and optimisation.

The method gives a first indication of what a specific technology is capable of within a complex system's context, explicitly allowing the analyst to identify the most life cycle relevant design parameters. The model's details can be increased according to the needs as the design progresses from the fuzzy to the detailed. The modular nature of the method can be used to supply flexible solutions specified individually to the different requirements and industries. Within an appropriate data environment the method is very suitable to be expanded to include life cycle costing as an integral part of the analysis.

8 Perspective

The concept introduced, apparently simple when contemplating only the individual steps, becomes a powerful analysis method, when the information for several products and their (sub-)components in the proposed form of mathematical models and parameterised inventories are linked together. This complex network allows an analyst to further understand the interrelationships of his/her design decisions in early design phases. In today's engineering environments the full potential may not be realised, due to the lack of data availability. Furthermore, the manual collection of data makes data itself prohibitively expensive for practical purposes. On the other hand, future integrated engineering environments will automate and systematise the exchange of relevant LCA and costing data along the supply chain, thus taking this method to its full potential.

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